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Simulation of dryout phenomenon and transient heat transfer performance of the once-through steam generator based on heat transfer partition

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ABSTRACT

A transient mathematical model is developed based on the distributed-parameter method by dividing the heat transfer regions of the secondary side of the once-through steam generator into single-phase preheating region, subcooled boiling region, nucleate boiling region, liquid deficient region (also known as post-dryout region) and single-phase superheating region in present work. And then it is used to simulate dryout phenomenon and transient heat transfer of the once-through steam generator. The results show that the developed mathematical model and method can be used to reasonably predict dryout phenomenon and transient heat transfer performance at different loads of the once-through steam generator. The heat transfer coefficient of the secondary side decreases sharply when dryout occurs, correspondingly the wall temperature shows a soaring trend and the maximum rising amplitude within present operating range is about 23 °C. The reduction of inlet enthalpy and mass flow rate of the primary side of the once-through steam generator both lead to a reduction of the outlet steam superheat and a downstream movement of the dryout point. The steam at the outlet cannot reach the superheating condition when the inlet enthalpy of the primary side decreases by 5%. The decrease of the inlet enthalpy of the secondary side within current range has little effect on the overall heat transfer performance, while the decrease of the mass flow rate of the secondary side leads to the upstream displacement of the dryout point and a rising outlet steam temperature.

1. Introduction

Once-through steam generator (OTSG) characterizing by compact structure, high efficiency, etc., is key heat exchanger undertaking the heat transfer between the primary side and the secondary side. Therefore, it has been paid wide attention in the application of integrated nuclear reactor (Shi et al., 2016; Wei et al., 2012). However, dryout deterioration will inevitably occur in the secondary side of the OTSG when the water of the secondary side experiences a flow and heat transfer process from single-phase subcooled water heat convection to single-phase superheated steam heat convection. If effective measures are not taken to control dryout, it may cause damage to the heat transfer tubes. Once the leakage accident of the heat transfer tube occurs, it will lead to serious consequences (Ferng and Chang, 2008; Liu et al., 2014). It can be seen that dryout is a significant limitation that directly affects the safety and reliability of the OTSG. Therefore, it is of great significance for the safe operation of the OTSG to investigate and analyze dryout phenomenon and corresponding transient heat transfer performance.

Based on the requirements of high efficiency, integration and small space, a lot of useful researches on the heat transfer performance, dryout phenomenon, and dynamic responses at different operating conditions, start-up and shut-down process of the OTSG have been carried out.

The first-order conservation equations and drift flow model were used to describe the two-phase flow region, and then the lumped parameter model of the steam generator was established to separately model the primary side and the secondary side. The primary side was regarded as a whole because the coolant of the primary side is always in a single-phase state, and the secondary side was divided into four regions: rising region, tube bundle region, downcomer channel and steam space, and then the variations of the steam generator parameters at different operating conditions were discussed (Strohmayer, 1982). Based on the mass,

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Nomenclature

English symbols

x	axial position of the heat transfer tube, m
L	axial height, m
T	fluid temperature, °C
c_p	specific heat capacity, J/(kg·°C)
m	mass flow rate, kg/s
t	time, kg/(m^3·s)
K	heat transfer coefficient, W/(m^2·°C)
M	fluid mass per unit axial height, kg/m
ΔT_s	wall superheat, °C
p	pressure of the secondary side, MPa
q	heat flux, MW/m^2
X_{dryout}	critical quality
$\dot{m}$	mass flux, kg/(m^2·s)

Greek symbols

λ	thermal conductivity, W/(m·°C)
μ	dynamic viscosity, N·s/m^2
σ	surface tension, N/m^2
ρ	density, kg/m^3

Subscripts

1	primary side
2	secondary side
in	inlet
out	outlet
wi	inner wall
wo	outer wall
s	saturation condition
i	*y*, *l*, *h*, *m or g*
y	single-phase preheating region
l	subcooled boiling region
h	nucleate boiling region
m	liquid deficient region
g	single-phase superheating region
f	liquid
v	steam

momentum and energy conservation equations, the lumped parameter mathematical model of helically coiled OTSG was developed to simulate the distributions of inlet and outlet key parameters (Li et al., 2008). Then the three conservation equations in the form of lumped parameter were developed based on the compressible flow model and incompressible flow model, respectively. And then it was proved that the compressible flow model is more suitable for the dynamic simulation of the OTSG (Wang et al., 2012).

The lumped parameter models with movable boundary used in above researches mainly focused on the variations of inlet and outlet thermal-hydraulic parameters of the primary and secondary sides, while the axial thermal-hydraulic characteristics of the two sides were paid less attention. Therefore, some researches on the local distributions of flow and heat transfer characteristics of the steam generator were carried out. The boundary between single-phase heat convection region and boiling heat transfer region was fixed by the temperature distribution curve, and it was found that the boundary moved to one end of the tube at low or high mass fluxes during the iterative calculation (Nariai et al., 1982). The U-tube steam generator of Daya Bay Nuclear Power Station was used as the prototype, and the one-dimensional homogeneous flow models for the coolant of the primary side, subcooled boiling region and nucleate boiling region of the secondary side, and the inner wall and outer wall of the heat transfer tube were developed based on the distribution parameter method, and then the steady heat transfer performance and the effect of tube leakage on the dynamic performance of the steam generator were investigated (Zhang et al., 2014). The porous media model and FLUENT software were used to establish the three-dimensional flow model of the secondary side of the steam generator for single-phase flow condition. Then the distributions of the velocity, temperature, pressure and density were obtained and it was verified that the method could be used to analyze the problems of flow-induced vibration and steam separators (Cong et al., 2014).

Considering that the heat transfer performance of the OTSG is completely different from that of the traditional U-tube natural circulation steam generator, the flow boiling process of the secondary side of the OTSG in which the fluid is heated from subcooled water to superheated steam is extremely complex and dryout inevitably occurs, while the fluid of the secondary side of the U-tube steam generator is only heated from subcooled water to saturated steam of nucleate boiling region and dryout does not occur. Therefore, scholars further conducted some researches on the thermal-hydraulic characteristics of OTSGs. The movable boundary model and the simulation code based on the fixed boundary model of the OTSG were developed, and the heat transfer regions were divided into three regions according to the fluid phase condition: single-phase subcooling region, two-phase region and single-phase superheating region. By comparing the simulation results with experimental data, it could be found that the movable boundary model is of high computational speed and precision, and is an ideal model for dynamic simulation of the OTSG (Yi et al., 2002). The heat transfer regions of the OTSG were divided into subcooling region, nucleate boiling region and superheating region, and the concept of effective heat transfer length was proposed to simulate the distributions of the inlet and outlet fluid temperature under disturbance (Zhu et al., 2012). In above researches, the overall heat transfer performance of the OTSG can be reasonably simulated, but they could not provide some reference for the effective control of dryout deterioration phenomenon because of ignoring the existence of dryout and post-dryout mist flow region in heat transfer partition process. The steady analysis codes were developed to investigate the thermal-hydraulic characteristics of the OTSG used in 300 MW SMART and 600 MW China Fast Reactor (CFR), respectively. And the developed codes could be used to reasonably calculate the distributions of the key parameters of the primary side, the secondary side and the tube after verification and optimization (Yoon et al., 2000; Sun et al., 2016).

To sum up, these useful researches can provide some reference for design and operation of OTSGs. However, the inlet and outlet thermal-hydraulic parameters of the primary and secondary sides were mainly focused on when the lumped parameter model was used to simulate the heat transfer performance of OTSGs, while the thermal-hydraulic characteristics at any arbitrary point of the two sides were paid less attention. Considering that two-phase flow and heat transfer of the secondary side has a significant influence on the axial distribution of the thermal-hydraulic characteristics during the actual operation, some researchers simulated the local thermal-hydraulic characteristics of the actual steam generator (Nariai et al., 1982; Zhang et al., 2014; Cong et al., 2014), such as heat transfer from single-phase heat convection of preheating region to boiling heat transfer of nucleate boiling region. But the research ranges have not been involved in dryout phenomenon and post-dryout heat transfer region. Some researchers also simulated